The Dynamical Evolution of Planetary Nebulae After the Fast Wind

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ABSTRACT

In this paper we explore the dynamics of ionization bounded planetary nebulae after the termination of the fast stellar wind. When the stellar wind becomes negligible, the hot, shocked bubble depressurizes and the thermal pressure of the photoionized region, at the inner edge of the swept-up shell, becomes dominant. At this stage the shell tends to fragment creating clumps with comet-like tails and long, photoionized trails in between, while the photoionized material expands back towards the central stars as a rarefaction wave. Once that the photoionized gas fills the inner cavity, it develops a kinematical pattern of increasing velocity from the center outwards with a typical range of velocities starting from the systemic velocity to ~ 50 km s^{-1} at the edges. The Helix nebula is a clear example of a planetary nebula at this late evolutionary stage.

Subject headings: Hydrodynamics—Stars: AGB and Post-AGB—Planetary Nebulae: general —Planetary Nebulae: individual (NGC 7293, NGC 6853, NGC 2867)

1. Introduction

High spatial resolution imagery in recent years have revealed a number of well developed planetary nebulae that exhibit a fragmented appearance of their shells with clumps and radial spokes, as it is the case of the famous Helix Nebula, NGC 7293 (Vorontsov-Velyaminov 1968; Meaburn et al. 1992; O'Dell & Handron 1996). Similar examples are the Dumbbell nebula, NGC 6853 (Manchado et al.1996; Meaburn et al. 2005a) and NGC 2867 (Corradi et al. 2003). Rayleigh-Taylor instabilities have been some times invoked as the cause of this fragmentation

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but with limited success (Burkert & O'Dell 1996). Alternatively, the effects of the ionizing radiation on the nebula have been shown by Capriotti (1973) and also by García-Segura & Franco (1996) and García-Segura et al.(1999) to be much more relevant in the fragmentation process of the nebular shell.

Recently, Meaburn et al. (2005b) have shown that the current kinematics of nebulae such as NGC 7293 cannot be explained by the classic "two-wind model" (Kwok 1982). Since NGC 7293 shows emission in He II and O [III] at very low velocities close to the central star, Meaburn et al. (2005b) concluded that only after the fast wind has switched off could this global velocity structure be generated. The absence of a fast stellar wind in NGC 7293 has been confirmed from observations with the IUE satellite (Perinotto 1983; Cerruti-Sola & Perinotto 1985) that failed to detect P-Cygni profiles from their central stars; likewise in the cases of NGC 6853 and NGC 2867. Furthermore, the lack of extended, soft x-ray emission from NGC 7293 (Guerrero et al. 2001) discards the presence of a "hot bubble" and the shocked, fast wind. In general, Cerruti-Sola & Perinotto (1985) found that the hotter the central stars are the least likely to have fast stellar winds, a result indicative of the rapid fading of the stellar wind as the central star evolves.

In this letter we present numerical calculations which show that the decay of the fast stellar winds produces self-consistently the fragmented structures and kinematics observed in evolved planetary nebulae.

2. Relevant Stellar Parameters

There are several dynamical studies of the evolution of PNs that include the effects of stellar evolution. Recently, Schönberner et al. (2005) have discussed the stellar evolution path for a 0.595 $M_\odot$ post-AGB, following the recommendation of Pauldrach et al.(1988) for the parameters of the central stellar wind. A Reimers' wind (Reimers 1975) is assumed during the short transition region from the AGB to the PN domain. In this model (see Figure 1 in Schönberner et al.2005), the mass loss rate begins with several 10^{-7} $M_\odot$ yr^{-1} for a period of 10^3 yr, decreasing down to 10^{-8} $M_\odot$ yr^{-1} , to finally reach values of 10^{-10} $M_\odot$ yr^{-1} after 10^4 yr; meanwhile the wind velocity increases from 10^2 to 10^4 km s^{-1} . After 10^4 yr the wind can be considered negligible (turn-around point). As initial condition, this calculation assume 4.3×10^{-5} $M_\odot$ yr^{-1} and $v_\infty = 10$ km s^{-1} for the AGB wind.

Also, Villaver et al. (2002a) have used the paths from Vassiliadis & Wood (1994) for 0.569 $M_\odot$, 0.597 $M_\odot$, 0.633 $M_\odot$, 0.677 $M_\odot$, 0.754 $M_\odot$ and 0.9 $M_\odot$, corresponding to initial values at the ZAMS of 1, 1.5, 2, 2.5, 3.5 and 5 $M_\odot$ respectively. The Vassiliadis & Wood's

(1994) models also use the Pauldrach et al.(1988) theoretical results to compute the mass loss rates and wind velocities from the AGB to the PN domain. In these models (Figure 2 in Villaver et al. 2002a), the fast wind is negligible (turn-around point) after 30×10^3, 10×10^3, 5×10^3, 2.5×10^3, 1×10^3, and 0.2×10^3 years respectively. The second model in Villaver et al. (2002a) is almost identical to the model used in Schönberner et al. (2005). The initial conditions (see Villaver et al. 2002b) corresponding to the end of the AGB winds are taken from Vassiliadis (1992), and are in the range of $4 \times 10^{-6} - 30 \times 10^{-6}$ M$_\odot$ yr^{-1} , and $11 - 15$ km s^{-1} .

Mellema (1994) has also used a model for a 0.598 M$_\odot$ post-AGB from Schönberner (1983), with similar stellar parameters as discussed above.

Given the range of possible parameters to consider in the stellar evolution tracks, stellar masses, mass loss rates and wind velocities, we have adopted in this study the following representative numbers: For the AGB winds, we have adopted a $v_\infty = 10$ km s^{-1} , $\dot{M} = 10^{-6}$M$_\odot$ yr^{-1} (model A) and $\dot{M} = 10^{-5}$M$_\odot$ yr^{-1} (model B). For the post-AGB wind, $v_\infty = 1,000$ km s^{-1} and $\dot{M} = 10^{-7}$M$_\odot$ yr^{-1} . These choices give wind momentum ratios of 10 (model A) and 1 (model B). We also have adopted 1,000 yr for the duration of the fast wind.

3. Simplified Hydrodynamical Simulations

The numerical experiment presented here (model B)(García-Segura et al.2006 discusses model A) includes two phases: in the first phase, a typical two-wind model scenario (Kwok 1982) where a fast wind sweeps up a slow wind is considered. For simplicity, this phase lasts 1,000 yr in the computation, but it could last longer or shorter depending of the particular track of stellar evolution. In the second phase, the fast wind is switched off, and the dynamical evolution is computed for a total of 8,000 yr. In both phases the photoionization is considered following the approach of García-Segura & Franco 1996 with a central star that emits $10^{45}s^{-1}$ ionizing photons. We have adopted this average value from Villaver et al. (2002a) (see their Figure 4), which is maintained for at least 10^4 yr. We have not considered in detail the temporal variation of the ionizing photons. However, Villaver's models show that the evolution of the nebulae are optically thick during the first few thousand years of the evolution. In this regime, our simple models provide a reasonable description of the location of the ionization front for the mass-loss rates that we have considered. A simple expanding spherical morphology is adopted for simplicity (i. e., no rotation, magnetic field, or anisotropic mass-loss events).

The simulations are performed with the hydrodynamical code ZEUS-3D (version 3.4) (Stone & Norman 1992; Clarke 1996), and details about the set up can be found in García-Segura et al.(1999), and García-Segura et al.(2005) for the self-expanding grid technique.

We perform the two-dimensional simulation in spherical polar coordinates (r, θ), with reflecting boundary conditions at the equator and the polar axis, and rotational symmetry assumed with respect to the latter. Our grid consist of 200×180 equidistant zones in r and θ respectively, with a radial extent of 0.1 pc (initially), and an angular extent of $90°$. The innermost radial zone lies at $r = 2.5 \times 10^{-3}$ pc from the central star.

Figures 1 and 2 show mosaics of snapshots of gas densities and photoionized gas densities covering 8,000 yr of the evolution for model B, each one separated by 1,000 yr. The first, top-left panel in Figure 1 shows progressively, starting from the origin of the grid, the fast, free expanding wind region, the terminal or reverse shock, the hot, shocked bubble, the swept-up shell with an outer, forward shock, and the slow wind. This is the classical view of a two-wind model. Vishniac (1983) or thin shell instabilities give the corrugate appearance of the swept-up shell (see García-Segura & Mac Low 1995 for further details). The rest of the panels show how the hot shocked bubble collapses after $\sim$ 6,000 yr and also show the expansion of the photoionized gas, once that the fast wind is switched off. The fragmentation of the swept-up shell follows the pattern imposed by the Vishniac instability, and its development and growth comes from the ionization-shock front instability (García-Segura & Franco 1996).

Figure 3 is a mosaic with snapshots of the radial velocities counterparts of Figure 1 and 2. The last two panels (bottom-right) show the global kinematics of the ionized gas after the collapse of the hot bubble in which it can be clearly appreciated that the gas close to the central star presents very small velocities, reaching practically inert conditions there, as it is found in the Helix nebula (Meaburn et al.2005b). Notice that these low velocities reach the central star region, and are not only a projection effect along the line of sight, as in models where the low velocity emitting regions are located in the inner edges of the swept-up shells (e. g., Marten & Schönberner 1991; Perinotto et al. 2004). The gas located at the border of the main nebula, shows larger velocities following the kinematics of a rarefraction wave.

The last panel of Figure 3 also shows that the neutral cometary globules immersed in the nebula present smaller velocities than the surrounding photoionized gas that has been accelerated by thermal pressure, while the extended sections of these neutral tails at further distances show larger velocities than the AGB wind due to the acceleration by the ionization-shock front. Model B is not shown in this letter, but it is discussed in García-Segura et al. (2006) where similar results are found.

In the simulations, the cometary globules originate in the neutral, swept-up shell of

piled up AGB wind, and so, they, or part of them must be excited by shocks. This is consistent with the detection of shock-excited molecular Hydrogen in the Dumbbell nebula (see Manchado et al. 2006). Once that the wind is switched off, the head of the globules are no longer confined in the swept-up shell by the pressure of the wind, and so, they become engulfed in the nebula. This is a novel result that previous hydrodynamical works had not solved (see for example García-Segura et al. 1999). Huggins et al.(1992) observed that the CO cometary globules in the Helix nebula show a smaller expansion velocity than the ionized gas, which is in line with our computations. However, the present numerical simulations are two-dimensional, and the limited resolution does not allow a quantitative analysis of the structures that are formed. Thus, quantitative details about velocities of the globules, number, sizes and masses, as well as the spoke-like pattern and its spatial frequency developed in the simulations are beyond the scope of this letter. However, the qualitative resemblance with cases like the Helix and the Dumbbell nebulae is remarkable and encouraging. Note for example, the cometary globules that develop in Figure 2, bottom-right, with bright photoionized heads, like the ones observed in the Helix (see also Figure 16 in O'Dell et al. 2004), and also the resemblance with the molecular, shock-exited long tails extending further out in the Dumbbell (Manchado et al.2006).

In this study, we have switched off the fast wind after the first 1000 years of evolution and followed the subsequent development finding for the first time a consistent representation of the fractured morphology and kinematic pattern often observed in planetary nebulae. The stellar wind is likely not to die-off as abruptly as in our simulations, although massive central stars evolve fast (e.g. see fig 3 in Villaver et al. 2002) and the behavior computed here should be a good approximation for those cases, as in the Helix nebula where the estimated central star mass is 0.93 $M_\odot$ (Górny et al. 1997). For the case of the evolution of low mass central stars, those are expected to take place in much longer times than the dilution of their surrounding nebulae. If this is the case, there should be a direct correlation between the fragmentation of a planetary nebula with the mass of the central star, and an anticorrelation with the detection of extended soft x-rays.

Additional numerical simulations at higher resolution, taking detailed account of the time dependent stellar evolution effects will allow a quantitative analysis of the shell structure as a result of the termination of the fast wind. Such calculations will be the subject of a future paper.

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Fig. 1.— Snapshots of gas densities covering 8,000 yr of the evolution of model B

Fig. 2.— Same as Figure 1 but for photoionized gas densities. The white line at 45° in the last panel correspond to the one-dimensional plot on figure 3

Fig. 3.— Same as Figure 1 but for radial velocities. A one-dimensional plot at 45° is also shown in the last panel at 8,000 yr.

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